The Link Between Climate Sensitivity Uncertainty and Understanding Cloud-Aerosol Interactions

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1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

The most fundamental challenge facing Earth System Science in the coming decade is to understand the climate sensitivity of the planet defined as the change in globally averaged surface temperature due to a doubling of CO_2. Agreement on this fundamental metric of climate change has been elusive since the first IPCC assessment. The values produced by the leading models of the 1990's ranged between 1.5 and 5 degrees. Now after the fifth assessment report, the range in predicted climate sensitivity remains between 2 and 5 degrees. What has become clear, however, is that one major cause of this spread in predicted climate sensitivity is the manner in which marine boundary layer (MBL) clouds change in a warmer world. Models predicting little change in MBL clouds under a warmer climate exhibit low sensitivity, in contrast to models predicting decreases in MBL clouds that have a high sensitivity. Other sources of climate sensitivity uncertainty are linked to inadequate representations of ice and mixed-phase cloud microphysics and transitions of cloud thermodynamic phase. As long as the question regarding cloud feedback remains open, so will the climate sensitivity question, and our ability to inform policy makers about Earth's climate over this and the next century will remain compromised. Putting it simply, Earth's climate sensitivity cannot be determined without first solving the problems associated with MBL and other clouds.

Changes to MBL clouds in a warming world have been difficult to predict because their macroscale characteristics such as cloud cover that evolves as global temperatures rise are largely due to changes in MBL dynamics driven by changes in the cloud fields themselves. These cloud fields are at once composed of myriad evolving cloud elements going through their individual lifecycles in 10's of minutes in response to local dynamical and thermodynamical forcings. The forcings in turn depend on how past cloud elements evolved and modified their environment through various processes such as mixing dry air from the free troposphere and downdrafts in precipitation. A foundational concern in this process is the number of cloud droplets nucleated in an updraft because droplet concentration affects the timing of precipitation onset and the vertical development of a cloud. These processes determines how a cloud element modifies the local thermodynamic and dynamic environment by mixing rain-cooled or dry air from the free troposphere into the marine boundary layer that subsequently drives the next sequence of cloud elements.

It has been known for nearly 4 decades that the characteristics of the aerosol particles (their number, size distributions and chemical properties) largely determine the number of droplets nucleated in an updraft of a given strength. If the aerosol concentrations are increased due either to natural or anthropogenic mechanisms, the cloud field and in particular the droplet size distribution, responds in a way that results in deeper and more reflective cloud elements that also take longer to rain because of more numerous and smaller droplets. It is unknown whether these microphysical perturbations persist or whether the cloud field adjusts via dynamical feedbacks as suggested by recent studies. The manner in which the cloud field evolves over time (due to specific aerosol forcings within certain dynamic and thermodynamic environments) can be simulated with high-resolution models, and parameterizations, in theory, can be formulated from such simulations. However, and this is the key issue, the accuracy of such predictions and the fidelity of resulting parameterizations are *unknown because observations do not exist to constrain the predictions*. Even though the dynamical feedbacks are critical to our ability to simulate the MBL, the important constraints that lend themselves to measurements are aerosol, cloud, and precipitation microphysics. Ultimately, data assimilation and modeling will need to go hand-in-hand with the advanced measurements, bridging these coupled processes.

Beyond the MBL cloud problem, the fifth IPCC assessment report stressed that the representation of aerosol–cloud interactions in mixed-phase and ice clouds is even less advanced than in liquid-only clouds. With thermodynamic phase affecting cloud opacity, evolution and precipitation characteristics, the poor understanding of the climatology and lifecycle of aerosol particles that can serve as ice nuclei is a glaring shortcoming.

Therefore, a prerequisite of accurately predicting climate sensitivity are observations that constrain the aerosol characteristics in the MBL, observations that constrain the updraft velocity at the base of MBL clouds, and a strategy to observationally characterize the number of cloud droplets that are nucleated at the base of MBL clouds, and for inferring the production of and characteristics of precipitation as a function of height in MBL clouds. Furthermore, improved constraints on aerosol size distributions and composition, cloud phase, ice microphysics and cold cloud precipitation are crucial to further reduce uncertainties associated with mixed-phase and ice clouds. We maintain that an observing system designed to retrieve these geophysical parameters must be an explicit goal of the succession of missions planned for the next decade. These measurements hold the key for predicting the Earth's climate sensitivity with reasonable confidence.

In short, our inability to observationally constrain global aerosol size and composition, cloud phase and ice and liquid microphysics severely limits advancement on nearly all issues related to reducing the intermodel spread in climate sensitivity.

Many of the above points were also made in a whitepaper that emerged from a community workshop held at NASA Ames Research Center in May of 2014. The document entitled "*Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics, and Radiation for the Coming Decade*", (available at https://espo.nasa.gov/home/content/NASA_SMD_Workshop), identifies a number of critical science questions to be addressed for our understanding of the Earth system to improve. Among these, the aerosol, cloud, radiation, and convection sections of the document generally agree that the understanding of aerosol, cloud, and precipitation processes within various circulation regimes represents our greatest challenge, and only observationally constraining those processes will bring improved understanding.

2. Why are these challenges/questions timely to address now especially with respect to readiness?

Observationally constraining aerosol cloud interaction as described above is both more necessary and also more practically attainable now for a confluence of reasons. Computing power has led to rapid advances in simulations of aerosol-cloud-precipitation processes. Global model runs are now possible at the cloud resolving scale, while large eddy simulations of cloud systems are feasible at grid spacings of a few meters. Measurement systems must keep pace with these capabilities. But the opposite is actually happening, with our measurement capabilities from space contracting as the A-Train begins disbanding in the 2017 timeframe, and no next generation suite of observing systems meeting the requirements identified above and keeping pace with the modeling community is being readied for launch.

The 2007 NRC Decadal Survey had recognized the observational needs identified here and recommended the Aerosol-Clouds-Ecosystem (ACE) Mission. ACE as presently envisioned in a recently completed whitepaper would be capable of addressing the observational constraints necessary to resolve cloud-aerosol interactions. NASA has continued to invest in rapidly maturing ACE-related technology to the point where an advanced suite of measurements would be much more capable than the A-Train or the European equivalent EarthCare slated to launch in 2018.

Therefore, the conjunction of advances in modeling capabilities and measurement technology make *solving* the aerosol-cloud problem for MBL and other types of clouds an attainable possibility in the coming decade.

3. Why are space-based observations fundamental to addressing these challenges/questions?

It is reasonable to ask whether global measurements are needed to constrain microphysical processes. Why, for instance, cannot suborbital or even ground-based measurements suffice? The issue is one of statistical robustness and accessibility. Often multiple processes compete or work in tandem and resolving process-level information from remote sensing measurements be they suborbital or space-based is challenging because poor spatiotemporal coverage limits contextual information. Therefore, only a global set of measurements collected over a period of years will allow us to develop the relevant statistics over diverse meteorological regimes and aerosol types, including the most distant regions of the planet where aircraft and ground-based assets are nearly impossible to deploy. While aircraft and ground observations for judicially-selected case studies will still be useful and even necessary for providing evaluation and validation of space-based estimates, and additional statistical constraints, only global measurements are capable of collecting the data volumes required to understand aerosol-cloud processes as a function of circulation regime.